

Gamma Ray Astronomy

Martin Pohl

Institut für Theoretische Physik, Lehrstuhl 4, Ruhr-Universität Bochum, 44780 Bochum, Germany

Abstract. This paper summarizes recent results in γ -ray astronomy, most of which were derived with data from ground-based γ -ray detectors. Many of the contributions presented at this conference involve multiwavelength studies which combine ground-based γ -ray measurements with optical data or space-based X-ray and γ -ray measurements. Besides measurements of the diffuse emission from the Galaxy, observations of blazars, γ -ray bursts, and supernova remnants this paper also covers theoretical models for the acceleration of radiating particles and their emission mechanisms in these sources.

1 Introduction

To date, γ -ray astronomy is a rapidly evolving field, the clearest indication of which is the fact that many reports in the AGN session were rewritten to include spectacular results obtained only a few weeks prior to the start of this conference.

This rapporteur paper covers 192 contributed papers on a range of topics in γ -ray astronomy drawn from the sessions OG 2.x. The classes of objects covered include supernova remnants (OG 2.2), pulsars and plerions (OG 2.2), active galactic nuclei (OG 2.3), Galaxy Clusters (OG 2.3), γ -ray bursts (OG 2.4). Also presented were results on diffuse γ -ray emission (OG 2.1) and on astroparticle physics (OG 2.7). Briefly summarized are reports on projects, instrumentation, and analysis techniques (OG 2.5).

2 Projects and instrumentation

Since the de-orbiting of the Compton Gamma-Ray Observatory (CGRO) in June 2000 no space-based γ -ray detector has been operational. During the Nineties the Energetic Gamma-Ray Experiment Telescope (EGRET) aboard CGRO

was very successful in detecting GeV γ -rays from around 70 AGN, 8 pulsars, and 170 sources not yet identified firmly with known objects (Hartman et al., 1999). EGRET has also measured the spectrum and the spatial distribution of the diffuse galactic γ -ray emission with unprecedented sensitivity and resolution (Hunter et al., 1997).

The planned successor to EGRET, the Gamma-ray Large Area Space Telescope (GLAST), will not be launched before the year 2006. GLAST will offer a factor of eight more sensitive area to γ -rays than did EGRET, which combined with a much larger field-of-view and a better energy and spatial resolution will provide a sensitivity gain by a factor of thirty compared with EGRET (Ormes and Digel, 2001).

During the time before GLAST becomes operational, two initiatives in satellite-based γ -ray astronomy are planned to provide astronomical data at GeV energies. The Italian AGILE satellite (Astro-rivelatore Gamma a Immagini LEggero) will offer a sensitive area similar to that of EGRET and an angular resolution somewhat better than EGRET (Mereghetti et al., 2001). The sensitivity of AGILE as a γ -ray detector will however be compromised by its limited energy resolution. The Alpha Magnetic Spectrometer (AMS), an instrument originally devised for the search for antimatter in cosmic rays, will also be able to identify γ -rays (Bertucci et al., 2001). For technical reasons AMS will mostly detect γ -rays with energies of a few GeV or higher, albeit with a sensitive area and an angular resolution slightly superior to those of EGRET. AMS can be expected to significantly contribute to our understanding of diffuse Galactic γ -ray emission, most notably the GeV excess, but may suffer from limited statistics in studies of point sources.

All GeV γ -ray experiments use pair production in thin foils of high- Z material to actually detect the γ -rays. Different techniques are used to track the e^+/e^- -pairs and to measure their energy, though. In principle the γ -ray energy threshold is around 10 MeV, but the short range of the pairs and small-angle scattering in the tracker significantly deteriorate the detector performance below 100 MeV. Towards high γ -ray energies self-vetoing and the finite thickness of

Correspondence to: M. Pohl (mkp@tp4.ruhr-uni-bochum.de)

the calorimeter can reduce the quality of measurement. The main problems with satellite-based γ -ray detectors, however, are the technical constraints which prohibit satellite payloads with an effective area of much more than a squaremeter. The flux of all cosmic γ -ray sources falls off with photon energy and therefore the scientific return of the γ -ray detectors at high photon energies is limited by statistics rather than inapplicability of the technique of measurement. GLAST will have an effective high energy limit of a few hundred GeV.

Photons with energies of a hundred GeV or higher generate electromagnetic showers in the earth atmosphere. The secondary particles thus produced move faster than the phase velocity of electromagnetic light and therefore emit optical Čerenkov-light that can be measured with suitable telescopes. Existing imaging Čerenkov telescopes such as WHIPPLE (Cawley et al., 1990), CAT (Barrau et al., 1998), HEGRA (Daum et al., 1997), CANGAROO (Hara et al., 1993), or TACTIC (Bhatt et al., 2001) have energy thresholds between 300 GeV and 2 TeV, but a sensitive area $\geq 10^3 \text{ m}^2$, because the atmosphere is used as the interaction site. Forthcoming or planned experiments will have lower energy thresholds and hence a higher sensitivity than the existing installations. Commencing operations in 2002, MAGIC (Lorenz et al., 2001) and VERITAS (Quinn et al., 2001) will observe the northern hemisphere while H.E.S.S. (Hofmann et al., 2001) and CANGAROO III (Mori et al., 2001) will study the southern sky. The MAGIC project will use a single large telescope optimized to provide a low energy threshold of 10–30 GeV, whereas the other three observatories will use multiple telescopes to simultaneously measure the Čerenkov-light of a shower, thus providing a very good hadron rejection and an excellent energy resolution.

Non-imaging observatories such as CELESTE (De Naurois et al., 2001), STACEE (Covault et al., 2001), Solar-2 (Tümer et al., 2001), GRAAL (Arqueros et al., 2001), and PACT (Chitnis et al., 2001) are now becoming operational. The very large mirror area of these observatories makes for a very low energy threshold of less than 30 GeV with large effective area, but the shower reconstruction and the hadron rejection are more difficult than for imaging observatories, for only the arrival time of the Čerenkov shower front can be measured.

All these Čerenkov telescopes provide a very good point source sensitivity, which allows to measure source variability on time scales of around one hour (Khélifi et al., 2001; Fegan et al., 2001). However, only one source can be observed at a time, and therefore the actual measurement of interesting behaviour of a source requires either luck or an indication of activity from other resources. The atmospheric Čerenkov telescopes are thus rather complementary to GLAST or to monitoring devices in the TeV energy range such as MILAGRO, which experiment detects γ -rays from a field nearly $2\pi \text{ sr}$ in extent by measuring Čerenkov-light of shower particles in a water pond (Sullivan et al., 2001). A second significant advantage of MILAGRO is the high duty-cycle of $\sim 100\%$ compared with the $\sim 10\%$ duty cycle of sunlight and moonlight limited observations with atmospheric Čerenkov

telescopes. The same is true for air shower arrays such as the TIBET air shower array (Amenomori et al., 2001a) or ARGO-YBJ (Assiro et al., 2001), which are composed of an array of particle detectors to measure the secondary particles in air showers produced by γ -rays.

The number and quality of upcoming γ -ray observatories offer good prospects for the future. Not only that the individual experiments will be much more sensitive than their predecessors, also the energy range of satellite-based and ground-based observatories will overlap, thus eventually providing complete coverage of the γ -ray spectra of sources from some 50 MeV to 10 TeV. The previously uncharted part of the spectrum, γ -ray energies between 10 GeV and 300 GeV, is particularly interesting, because leptonic γ -ray emission from supernova remnants should show a spectral peak in νF_ν representation, because competing models for γ -ray emission from pulsars predict different spectra, and because the infrared background light out to a redshift of $z \approx 0.5$ should be measurable by virtue of absorption effects in AGN γ -ray spectra.

3 Diffuse galactic emission

Why is it interesting to study diffuse galactic γ -rays? This emission is produced in interactions of cosmic rays with gas and ambient photon fields and thus provides us with an indirect measurement of cosmic rays in various locations in the Galaxy. A significant fraction of the diffuse galactic γ -rays is supposedly produced in decays of neutral pions following inelastic collisions of cosmic ray nucleons. Leptonic emission is particularly important at γ -ray energies below 100 MeV, where bremsstrahlung is presumably the main emission mechanism. Inverse Compton scattering of relativistic electrons on soft ambient photons is expected to provide γ -rays with a hard spectrum, thus eventually dominating over the π^0 -decay γ -rays at high energies (Porter & Protheroe, 1997). Measurements of diffuse galactic TeV γ -rays therefore constrain the cosmic ray electron spectrum at multi-TeV energies.

Recent observations made with the EGRET instrument on the Compton Gamma-Ray Observatory of the diffuse Galactic γ -ray emission reveal a spectrum which is incompatible with the assumption that the cosmic ray spectra measured locally hold throughout the Galaxy (Hunter et al., 1997). The spectrum observed with EGRET below 1 GeV is in accord with, and supports, the assumption that the cosmic ray spectra and the electron-to-proton ratio observed locally are uniform, however, the spectrum above 1 GeV, where the emission is supposedly dominated by π^0 -decay, is harder than that derived from the local cosmic ray proton spectrum. This is the well-known GeV excess.

3.1 The GeV excess

An interesting question is whether or not the GeV excess extends to TeV energies. WHIPPLE and HEGRA have ob-

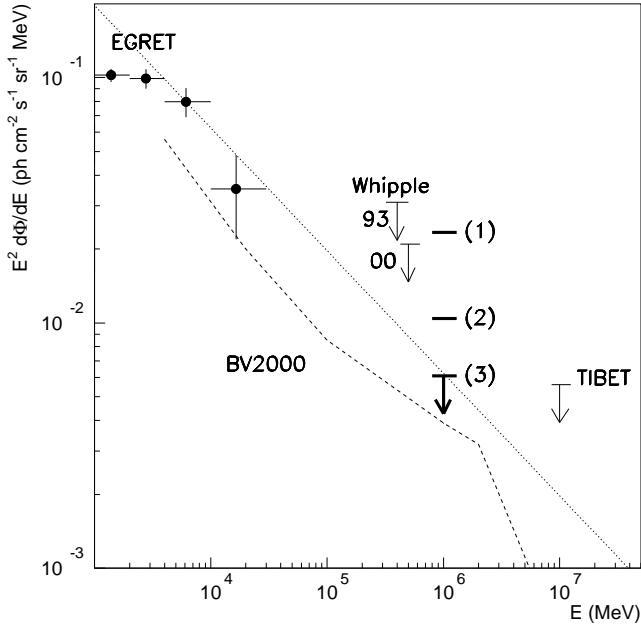


Fig. 1. Upper limits for the diffuse Galactic γ -ray intensity derived by various TeV γ -ray observatories (taken from Lampeitl et al. (2001)). The HEGRA upper limits for the region $38^\circ < l < 43^\circ$, $|b| \leq 2^\circ$ vary depending on what fraction of γ -rays is assumed to be due to diffuse Galactic emission (Aharonian et al., 2001a). Label 1 refers to all γ -rays, label 2 to an independent data set for background subtraction, and label 3 to $|b| \geq 2^\circ$ data as background estimate. Also shown is the EGRET flux for $35^\circ < l < 45^\circ$, $|b| \leq 2^\circ$, WHIPPLE upper limits for $38.5^\circ < l < 41.5^\circ$, $|b| \leq 2^\circ$ (Reynolds et al., 1993; LeBohec et al., 2000), and the TIBET upper limits (Amenomori et al., 1997). The upper limits weakly depend on the spectral index in the respective energy range. The dotted line is an extrapolation of the EGRET spectrum with an index of 2.5. The dashed line refers to a model calculation by Berezhko & Völk (2000) that is explained in the text.

served a small field in the Galactic plane at $l \approx 40^\circ$. The resulting spectrum of the diffuse γ -ray emission in that field is shown in Fig. 1. An upper limit at 10 TeV from the TIBET array is also shown, which however can not directly be compared with the results from the imaging Čerenkov telescopes, for it represents the γ -ray flux from a much larger part of the sky. The same restriction applies to new results from the TIBET II and TIBET HD arrays presented at this conference (Amenomori et al., 2001b).

The upper limits for diffuse Galactic γ -ray emission in the TeV energy range slightly depend on the spectral index in the respective energy range. They also depend on what fraction of observed γ -rays is attributed to the Galactic emission. Nevertheless it appears that the spectrum of diffuse Galactic radiation between a few GeV and a TeV can not be harder than a power law with a photon index of ~ 2.4 , which constrains published models of the GeV excess.

Pohl & Esposito (1998) have argued that the local cosmic ray electron spectra would not be representative for the Galaxy, if the electron were solely accelerated in supernova

remnants (SNR). If the average electron spectrum in the Galaxy is harder than that measured locally, then the correspondingly hard spectrum of the inverse Compton component could explain the GeV excess. The same basic conclusion was drawn in a later study by Strong, Moskalenko and Reimer (2000). In these models the inverse Compton spectrum is harder than E^{-2} at a few GeV and displays a slow softening at higher energies arising from the transition from the Thomson regime to the Klein-Nishina regime for infrared target photons. The inverse Compton spectrum would therefore violate the upper limits from WHIPPLE, HEGRA, and TIBET, if the SNR as the assumed sources of cosmic ray electrons would produce single power law particle spectra extending to electron energies higher than about 10 TeV. The available evidence for electrons with energies of 10 TeV or higher in SNR comes from observations of non-thermal X-ray continua which are interpreted as synchrotron radiation (Koyama et al., 1995). It is interesting to note that for all SNR the observed non-thermal X-ray flux is below extrapolations of the radio synchrotron spectrum (Reynolds & Keohane, 1999), which indicates that SNR do not produce electrons with single power law particle spectra extending to electron energies higher than about 10 TeV. The upper limits for diffuse galactic TeV γ -rays are therefore not in conflict with hard inverse Compton models of the GeV excess.

It is possible that cosmic ray nucleons also contribute to the GeV excess. Berezhko & Völk (2000) have calculated the γ -ray yield of cosmic rays before escape from their sources. The γ -ray spectrum produced within the sources would be harder than that of truly diffuse galactic γ -rays and thus unresolved sources of cosmic rays should contribute significantly at TeV energies, but would presumably not explain the GeV excess (see Fig. 1).

Büsching, Pohl and Schlickeiser (2001a,b) have investigated a dispersion in the cosmic ray source spectra such that the SNR would produce power-law spectra with varying indices. Then the interstellar cosmic ray spectrum should display a curvature which could explain the GeV excess, provided the spectral dispersion in the sources is sufficiently strong. Speculative though Büschings model may appear, the radio spectra of SNR indicate that a spectral dispersion exists (Green, 2001), if somewhat smaller than required to explain the GeV excess in total. If his model was right, then the upper limits for the TeV γ -ray intensity would require cosmic ray source spectra modified or cut off at about 100 TeV.

3.2 Low energy γ -rays

Dogiel, Schönfelder, and Strong (2001) have discussed the hard X-ray and soft γ -ray emission from the Galactic ridge, which, if interpreted as diffuse emission and not caused by unresolved sources, indicates the presence of a substantial flux of low energy cosmic rays. These authors find electron bremsstrahlung more likely than proton bremsstrahlung as the main radiation mechanism. More likely though an electron origin appears, the required cosmic ray electron source power would exceed the kinetic power provided by super-

novae and OB stars, suggesting that the 10 keV – 200 keV continuum emission from the Galactic ridge is still far from being understood.

4 Galactic sources

4.1 Supernova remnants

SNR are considered the most likely sources of galactic cosmic rays, either as individual accelerators or by their collective effect in superbubbles (Bykov, Gustov and Petrenko, 2001). Observational evidence in favor of this scenario has been found only for cosmic ray electrons, not for the nucleons.

Three shell-type SNR have been detected at TeV γ -ray energies so far. SN 1006 has been reobserved with CANGAROO with a flux consistent with the previously published result (Hara et al., 2001). Also in the new observations only the north-eastern rim is seen in TeV γ -rays. Recent observations of RX J1713-3946 with the 10m-telescope CANGAROO-II have yielded a detection with about 8σ significance and have thus confirmed the earlier measurement (Enomoto et al., 2001). The HEGRA array of Čerenkov telescope has detected TeV γ -rays from Cassiopeia A (Pühlhofer et al., 2001), if with 0.03 Crab above 1 TeV at a flux much lower than those reported for the two southern remnants.

All three shell-type SNR detected so far show non-thermal X-ray emission, which presumably is synchrotron radiation. It is known that the synchrotron radiating electrons would inverse-Compton scatter the microwave background to TeV γ -ray energies with a flux depending only on the X-ray flux and the magnetic field strength within the remnant (Pohl, 1996), provided both are measured at photon energies corresponding to the same electron energy. For the two southern remnants SN 1006 and RX J1713-3946 a significant contribution of γ -rays from hadronic interactions appears unlikely on account of the low density environment in which the remnants reside.

4.1.1 SN 1006 and RX J1713-3946

We have already noted that for all SNR the observed non-thermal X-ray flux is below the extrapolation of the radio synchrotron spectrum (Reynolds & Keohane, 1999), implying a cut-off in the cosmic ray electron spectrum. The actual cut-off energy would depend on the magnetic field strength, for it is measured in synchrotron frequency. The interesting question of whether or not the cut-off would be caused by energy losses, implying whether or not a similar cut-off must be expected in the cosmic ray nucleon spectra, is also a question of the magnetic field strength, for synchrotron radiation is the main energy loss channel.

Two important issues need to be addressed:

– Are the X-ray and TeV γ -ray spectra of SN 1006 and RX J1713-3946 compatible with each other in the sense of both being produced by the same particles? If that was the

case, it would confirm our notion of an inverse Compton origin of the γ -rays and we could indeed use the TeV flux as a measure of the magnetic field strength.

– Is the magnetic field strength thus determined such that the high energy cut-off in the electron spectra can be caused by synchrotron energy losses? If that was not the case, the cause of the cut-off would have to be intrinsic to the actual acceleration process and therefore also affect the cosmic ray nucleon spectra, which then would not be single power laws up to the knee at a few PeV.

Tanimori et al. (2001) find the γ -ray spectrum of SN 1006 between 1.5 TeV and 20 TeV well described by a power law

$$J(E) = (1.1 \pm 0.4) 10^{-11} \left(\frac{E}{\text{TeV}} \right)^{2.3 \pm 0.2} \text{TeV}^{-1} \text{cm}^{-2} \text{sec}^{-1} \quad (1)$$

When assuming a power law with exponential cut-off for the electron spectrum a fit of the combined radio, X-ray and γ -ray data is obtained with a cut-off energy $E_c \simeq 50$ TeV and a magnetic field strength $B \simeq 4 \mu\text{G}$ (see Fig.2). Allen et al. (2001a) have carefully analyzed the X-ray spectrum between 0.12 keV and 17 keV and find that the best model includes a thermal component and a broken power law component ($s_1 = 2.08 \pm 0.14$, $s_2 = 3.02 \pm 0.17$, and the break energy $E_c = 1.85 \pm 0.2$ keV) to describe the non-thermal continuum. Given the best-fit $B \simeq 4 \mu\text{G}$ of Tanimori et al. (2001), a γ -ray energy of 5 TeV would correspond to an X-ray energy of 0.4 keV. Based on their findings for the non-thermal part of the X-ray spectrum and the earlier γ -ray measurements (Tanimori et al., 1998), Allen et al. (2001a) have also presented a fit to the multi-band spectrum of SN 1006. With their parameters $B \simeq 10 \mu\text{G}$ and $E_c \simeq 20$ TeV a γ -ray energy of 5 TeV would correspond to an X-ray energy of 1 keV. The γ -ray spectrum measured with CANGAROO is statistically well defined below 10 TeV and thus has to be compared to the low energy X-ray spectrum with which it agrees. The compatibility of the X-ray and γ -ray spectra of SN 1006 supports our notion of an inverse Compton origin of the γ -rays. A confirmation would require the observation of corresponding curvature in the X-ray and TeV γ -ray spectra, though.

The magnetic field strength of $B \simeq 4 \mu\text{G}$ found by Tanimori et al. (2001) is disturbingly low, for the magnetic field in the rim should be compressed. The local upstream field around SN 1006 would have to be $B_{\text{up}} = 1 - 2 \mu\text{G}$ depending on orientation. We can calculate the e-folding acceleration time for diffusive shock acceleration with the diffusion coefficient $D = \eta D_{\text{Bohm}}$, $\eta \geq 1$, written in units of the Bohm diffusion coefficient $D_{\text{Bohm}} = cr_g/3$ with r_g as the Larmor radius of the electrons. Then

$$\tau_{\text{acc}} \simeq \frac{4D}{v_{\text{shock}}^2} \simeq (600 \text{ years}) \eta \frac{\left(\frac{E}{50 \text{ TeV}} \right)}{\left(\frac{B}{4 \mu\text{G}} \right) \left(\frac{v_{\text{shock}}}{3000 \text{ km/sec}} \right)^2} \quad (2)$$

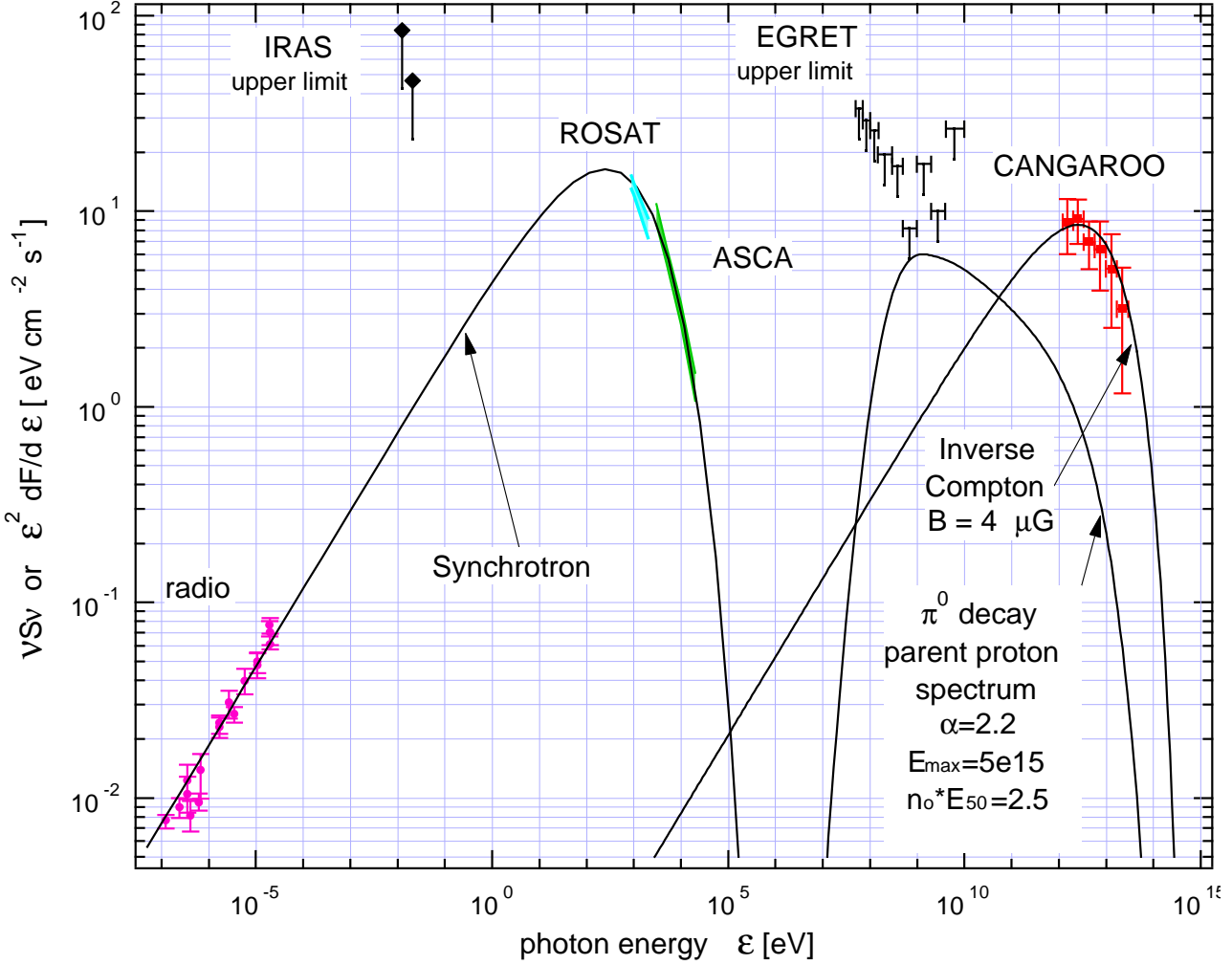


Fig. 2. Multi-band spectrum of energy flux observed from the north-eastern rim of SN 1006, where observed fluxes or upper limits of radio (Reynolds, 1996), infrared, soft X-ray (estimated from Willingale et al., 1996), hard X-ray (Ozaki, 1998), GeV γ -rays, and TeV γ -rays are presented (taken from Tanimori et al. (2001)). The solid lines represent their fits based on an inverse Compton model and π^0 -decay.

The acceleration time is similar to the age of the remnant for Bohm diffusion, i.e. $\eta = 1$. In the general case $\eta \gg 1$ the diffusive shock acceleration would not operate sufficiently rapid to provide electrons with 50 TeV within the age of SN 1006. If the magnetic field strength was substantially higher than $4 \mu\text{G}$, the acceleration time would be correspondingly smaller. As a result electron acceleration to 50 TeV within the time given would appear more feasible.

Van der Swaluw & Achterberg (2001) have combined hydrodynamical calculations of the evolution of a young shell-type SNR with an algorithm, which simultaneously calculates the associated particle acceleration in the test-particle approximation. These authors have not modelled the TeV spectrum in parallel to the X-ray spectrum. Nevertheless, they find that at an age of 1000 years a substantial fraction of accelerated electrons would have escaped from the regions of compressed magnetic field in the rims of SN 1006. While all electrons would comptonize the microwave background to TeV energies, only a fraction of them would emit syn-

chrotron radiation in a high magnetic field region. It is actually possible to obtain a fit to the multi-band spectrum of SN 1006 by assuming that the magnetic field occupies only 40% of the volume filled with cosmic ray electrons (Allen et al., 2001b). In this case the best-fit parameters would be $B \simeq 40 \mu\text{G}$ and $E_c \simeq 10 \text{ TeV}$. The electron energy loss time scale for synchrotron radiation at the energy E_c would be 900 years and thus similar to the age of the remnant. The acceleration time (Eq.2) would be similar or smaller than both the age and the energy loss time for a diffusion coefficient

$$\tau_{\text{acc}} \leq \tau_{\text{loss}} \simeq \tau_{\text{age}}$$

$$\Rightarrow \quad \eta \leq 75 \left(\frac{v_{\text{shock}}}{3000 \text{ km/sec}} \right)^2 \quad (3)$$

which would comfortably allow diffusive shock acceleration to accelerate electrons to the energies observed for a fair range of intensities of electromagnetic turbulence. Allen et al. (2001b) have assumed the extreme case of a vanishing

magnetic field in part of the volume. A realistic scenario would foresee a compressed magnetic field in the rims of the remnant and a lower (by a factor of a few) magnetic field strength outside the rims of SN 1006. Then we can expect $B \approx 20 \mu\text{G}$ in the rims, $E_c \approx 15 \text{ TeV}$, and $\tau_{\text{loss}} > \tau_{\text{age}}$.

We can therefore conclude that the electron spectrum in SN 1006 is probably not significantly modified by energy losses on account of the energy loss time being similar or larger than the age of the remnant. If cosmic ray nucleons were accelerated in parallel to the electrons, their spectrum would presumably show the same cut-off energy E_c as does the electron spectrum. Is it possible that during the later evolution of SN 1006 nucleons are accelerated to the knee at a 1000 TeV?

In the standard hydrodynamical model of SNR their evolution has a first phase, in which the expansion proceeds with constant velocity, followed by the so-called Sedov phase, during which the outer shock decelerates. The deceleration of the shock causes diffusive shock acceleration to operate less efficiently (see Eq.2), so that the maximum particle energy can increase only by a factor of a few during the Sedov phase. The question whether or not SN 1006 can accelerate cosmic ray nucleons to the knee is therefore linked to the question whether or not SN 1006 is already in the Sedov phase; a question to which I can not give a firm answer.

4.1.2 Cassiopeia A and Tycho

The supernova remnant Cassiopeia A differs from SN 1006 and RX J1713-3946 in that the supernova blast wave is expanding into a wind bubble and shell system from the previous wind phases of the progenitor star (Borkowsky et al., 1996). The matter density and the magnetic field strength in the upstream region of the outer shock are those of a red supergiant wind and not those commonly found in the interstellar medium. Cas A also shows a non-thermal hard X-ray continuum (Allen et al., 1997), which would imply high energy γ -ray emission from inverse Compton scattering. However, we must expect that both the γ -ray flux and the cut-off energy in the γ -ray spectrum are much less than for SN 1006 and RX J1713-3946 on account of the much higher magnetic field strength in Cas A, for which estimates for the magnetic field strength at the shock and in the downstream region suggest $B_d \simeq 1 \text{ mG}$ (Atoyan et al., 2000a).

The measured γ -ray flux and spectrum of Cas A are shown in Fig.3. Because of the moderate statistical significance of the overall detection, the spectral index is only poorly constrained. Also shown in the figure are model spectra based on calculations by Atoyan et al. (2000b). To be noted from the figure is that the predicted flux from π^0 -decay exceeds the observed flux (the prediction was made prior to the actual detection). The problem is that the expected absolute flux level of π^0 -decay γ -rays is not well determined in the context of general acceleration models. One of the crucial but poorly known parameters is the injection efficiency, with which suprathermal protons are injected at the shock front. In contrast to the electrons, for which the non-thermal X-ray

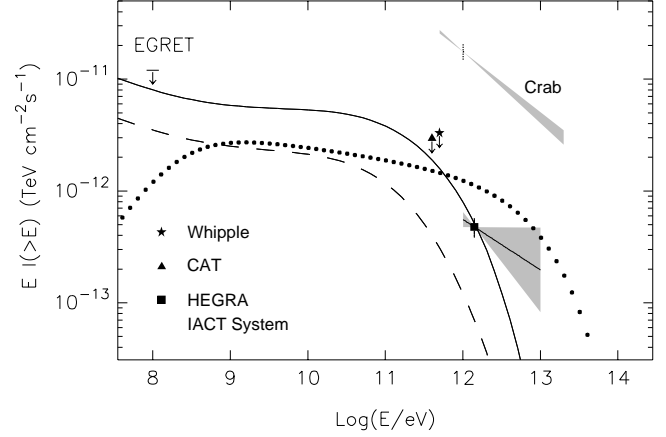


Fig. 3. The measured TeV γ -ray flux and spectral index of Cas A in the context of model predictions (taken from Pühlhofer et al. (2001)). The shaded area shows the 1σ error range for the measured spectral distribution under the assumption of a power law spectrum. Also indicated are the upper limits measured by EGRET, WHIPPLE (Lessard et al., 1999), and CAT (Goret et al., 1999). The data are compared with model predictions published by Atoyan et al. (2000b). The dotted curve represents a model spectrum for the γ -ray flux arising from π^0 -decay. The solid and the dashed line show the predicted inverse Compton plus bremsstrahlung spectra for two different parameter sets.

flux can be used as a primer for the electron flux, whatever the micro-physics at the acceleration site, the high energy cosmic ray nucleons do not reveal themselves in any observable channel other than γ -ray emission.

The injection efficiency does affect the overall efficiency of SNR in transferring their bulk kinetic energy to a few high energy cosmic rays. A high injection efficiency, as assumed by Atoyan et al. (2000b), would provide SNR with sufficient cosmic ray source power to constantly replenish the galactic cosmic rays. The data of Cas A suggest that some crucial parameters of the acceleration process are actually less favorable than assumed in the theoretical studies. To date we can not say, whether or not the TeV γ -ray data are in conflict with our notion that SNR accelerate the bulk of cosmic ray nucleons to PeV energies, but the situation is getting tight.

A high cosmic ray density in the remnants also implies backreactions of the cosmic rays on the acceleration process, one of which is a modification of the shock compression ratio caused by the pressure and energy density of the cosmic rays. Berezhko, Pühlhofer and Völk (2001) have presented a calculation of non-linear particle acceleration in Cas A. They have determined the injection rate for electrons by a fit of the radio to X-ray spectrum. The proton injection required to fit the observed TeV γ -ray spectrum of Cas A would be more than an order of magnitude less than the electron injection rate at the same energy. It has been suggested that in a quasi-perpendicular shock electrons can be efficiently injected, whereas proton injection is suppressed (Malkov & Drury, 2001). On the other hand, turbulence in the progenitor wind and at the interface with swept-up material should

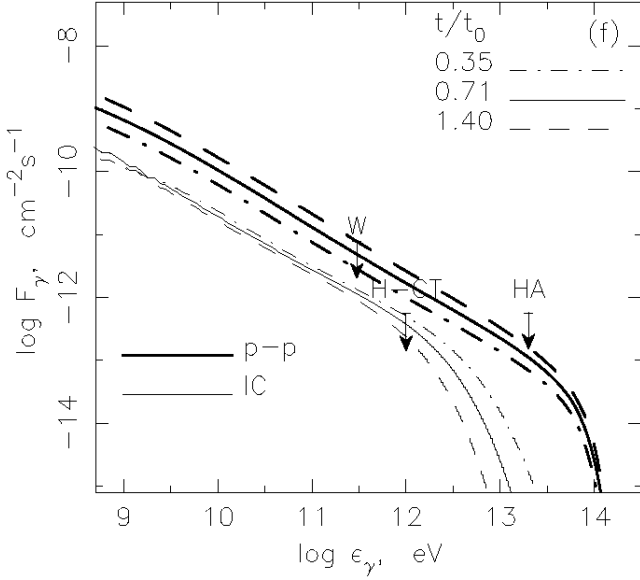


Fig. 4. The upper limits for TeV γ -rays from Tycho's SNR in comparison with the temporal evolution of γ -ray emission according to the model of Völk et al. (2001), from where the figure has been taken. The flux limits are W: WHIPPLe (Buckley et al., 1998), H-CT: HEGRA IACT system (Aharonian et al., 2001b), and HA: HEGRA AIROBICC (Prah et al., 1997). The modelled γ -ray spectra are shown for three evolutionary phases with the solid lines corresponding to the current stage of Tycho's evolution. The time t_0 marks the turn-over into the Sedov phase.

lead to many field lines being locally shock-parallel, thus allowing efficient proton injection at some parts of the shock. Clearly, more studies of the microphysics of particle injection at the shocks are needed.

No γ -ray emission has been detected from Tycho's SNR so far. HEGRA has established a very low 3σ upper limit of 0.03 Crab above 1 TeV (Aharonian et al., 2001b). In X-rays Tycho shows a thermal spectrum with strong lines and a bremsstrahlung continuum, but also a hard X-ray tail (Petre, Allen and Hwang, 1999), which presumably is of non-thermal origin. If we interpret the apparently non-thermal X-ray emission as synchrotron radiation, the upper limit for the TeV γ -ray flux implies a lower limit for the magnetic field strength with $B \geq 20 \mu\text{G}$, when the hard X-ray tail is extrapolated to lower X-ray energies, or $B \geq 6 \mu\text{G}$, when the non-thermal X-ray flux is estimated by modelling ASCA data (Hwang et al., 1998).

Völk et al. (2001) have used a nonlinear kinetic model of cosmic ray acceleration similar to the one applied to Cas A (Berezhko, Pühlhofer and Völk, 2001) to describe the properties of Tycho's SNR and to model the γ -ray emission. These authors argue that a magnetic field strength $B_0 = 40 \mu\text{G}$ in the upstream region and consequently $B_d \approx 200 \mu\text{G}$ in the downstream region is required to reproduce the synchrotron spectrum from radio to X-ray frequencies. In such strong magnetic fields high energy electrons in the downstream region are subject to radiative energy losses on a time scale

much shorter than the age of remnant. Therefore the electron spectrum displays a turnover to a softer power law at about one TeV with a spectral index change $\Delta s = 1$. The spectral indices of the TeV scale γ -ray spectra of inverse Compton scattering and π^0 -decay are then similar, however, the inverse Compton spectrum cuts off at a much smaller energy than does the π^0 -decay spectrum, as shown in Fig. 4. As in case of Cas A the expected hadronic γ -ray flux exceeds the observed value or limit, if for Tycho only by a factor of ten. Presumably the cause of that discrepancy is the same in both cases. The overprediction of the hadronic TeV γ -ray flux from Cas A and Tycho also compromises corresponding model predictions for hadronic γ -ray emission from SN 1006 (Berezhko, Ksenofontov and Völk, 2001).

4.2 Unidentified EGRET sources

EGRET has left a legacy of about 170 sources not yet identified firmly with known sources. Various population studies have been performed to search for correlations with classes of galactic objects. It has been noted only recently that very much care has to be exercised in these studies to account for systematic effects arising from the uneven exposure distribution and the structured galactic foreground emission (Reimer & Thompson, 2001). Searches for TeV γ -rays in the EGRET error boxes have not been successful so far (Fegan, Weekes et al., 2001).

It has been suggested that some of the unidentified EGRET sources are SNR (Esposito et al., 1996). A careful study shows that the spectra of well observed SNR candidates, associated with CTA 1, W28, IC443, and γ Cygni, are suggestive of a pulsar origin rather than young cosmic rays in shell-type SNR (Reimer & Bertsch, 2001). It is in fact possible that a number of unidentified γ -ray sources are actually pulsars born in the local star-forming region Gould's belt (Perrot & Grenier, 2001).

4.3 Pulsars and plerions

To date eight pulsars have been identified in the EGRET data on account of pulsed emission. There are two competing models for the production of pulsed γ -rays: the polar cap model (Daugherty & Harding, 1996) and the outer gap model (Hirotani, 2001), which may be observationally distinguished in the energy range between 3 GeV and 30 GeV. The extent of pulsed emission to very high γ -ray energies is a unique prediction of the outer gap models, and is not permitted by polar cap models. The non-imaging Čerenkov telescopes STACEE (Oser et al., 2001) and CELESTE (Dumora et al., 2001) have now established upper limit for the pulsed flux of the Crab at γ -ray energies of 190 GeV and 60 GeV, respectively. In their final configurations these two experiments will operate with substantially lower energy thresholds, as will do MAGIC, and thus will allow observational tests of the outer gap models.

There are a handful of pulsar-powered SNR with synchrotron nebula, so-called plerions. The Crab nebula is the pro-

totoplerion and serves as a standard candle in high energy astrophysics. Unpulsed γ -ray emission, which is commonly interpreted as being caused by inverse Compton scattering, can be detected up to about 20 TeV (Aharonian et al., 2000; Amenomori et al., 2000).

In case of PSR 1706-44/G343.1-2.3 the energy density of the synchrotron radiation in the nebula is less than that of the microwave background. Because the latter is known, quantitative estimates of the unpulsed TeV emission can be made (Aharonian et al., 1997). Earlier measurements of PSR 1706-44 with CANGAROO (Kifune et al., 1995) and the Durham Mk6 telescope (Chadwick et al., 1998) have indicated a TeV flux, which is an order of magnitude higher than predicted. Recent measurements with CANGAROO II have confirmed the high flux level and spectrum (Kushida et al., 2001), so that our problem to understand the source persists.

5 Active galactic nuclei

Why is it interesting to study γ -rays from active galactic nuclei (AGN)? These sources show very intense emission, which in many cases is variable. The variability has been observed on all time scales accessible with the available measurement techniques down to about one hour (see Fig.5). It should be noted that the AGN detected in the GeV to TeV range emit a significant, if not dominant, fraction of their luminosity in the form of γ -rays, indicating that with measuring γ -rays we actually study the main energy transfer processes in these objects.

A many studies suggest a flux correlation between X-ray and TeV γ -ray emission of AGN, which, if real, would allow a complementary view of the radiating particles, whatever their nature.

TeV γ -ray astronomy also provides means to probe the intergalactic infrared background radiation by measuring the absorption due to photon-photon pair production.

The types of AGN detected at high energies, which include flat-spectrum radio quasars (FSRQ) and BL Lacertae objects (BL Lacs), are collectively referred to as *blazars*. The broadband emission from blazars from radio wavelengths to the UV – or even X-rays in some cases – is apparently dominated by highly beamed, incoherent synchrotron radiation produced in a relativistic jet aligned closely to the direction to the observer. The relativistic beaming results in a strong amplification of the apparent luminosity and a reduction of the apparent variability time scales. It also explains the frequent observations of superluminal motion in these sources. In blazars γ -ray observations reveal a second component of the spectrum which does not connect smoothly with the low energy component. The multiband spectrum of blazars thus has a double hump shape with the second component peaking at energies between a few MeV and a few TeV. The underlying radiation mechanism of the high energy component is still the subject of debate, as is the nature of the particles causing the radiation. Nevertheless it has been recognized that inverse Compton scattering by the synchrotron radiat-

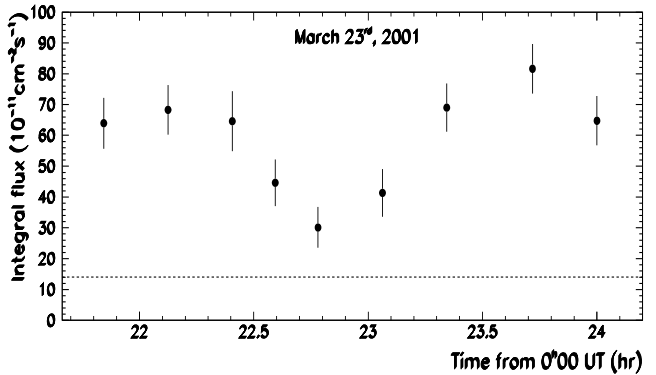


Fig. 5. Mkn 421 integral flux above 250 GeV during the night of March 23rd, 2001, as observed with the CAT telescope (taken from Khélifi et al. (2001)). Each point indicates a ~ 15 min observation, the dashed line shows the flux level of the Crab nebula. The γ -ray flux from Mkn 421 varies by more than 2 Crab within one hour.

ing electrons should contribute to the γ -ray component in the multiband spectra of blazars.

EGRET has detected about 70 blazars in the energy range between 100 MeV and 10 GeV, most of which are FSRQ. The imaging atmospheric Čerenkov telescopes have observed a handful of blazars in the TeV energy range, most of which are BL Lacs. BL Lacs are noted for a very small contribution of thermal emission in the Optical on account of the small equivalent width of lines in the spectrum. It is possible that in BL Lacs the ambient soft photon field is much more dilute than in FSRQ, implying that internal absorption by pair production would be less efficient and that inverse Compton scattering of these photons would not play an important rôle, both compared with FSRQ and with inverse Compton scattering of synchrotron photons produced in the jet, the so-called synchrotron-self-Compton (SSC) process. It appears that soft photons from a possibly existing dust torus are particularly important in FSRQ (Donea & Protheroe, 2001), depending on the geometrical structure of the torus (Arbeiter et al., 2001).

The threshold energy for pair production is identical to the energy at which the transition between the Thomson regime and the Klein-Nishina regime in inverse Compton scattering occurs. Georganopoulos et al. (2001) have extended earlier treatments of the problem (Böttcher et al., 1997) and have shown that the transition to the Klein-Nishina regime causes a turn-over to softer γ -ray spectra at higher energies, which can seriously compromise interpretations of the spectral energy distribution in the framework of an SSC origin of the high energy radiation.

Very little is known on the origin of the radiating particles in the jets of AGN. Are the synchrotron radiating electrons the primary particles, i.e. directly accelerated in the jets, or are they secondary particles produced in inelastic interactions of high energy nucleons? In the latter case neutrinos would be produced in parallel to the γ -rays. Schuster et al. (2001) have calculated the neutrino yield for a particular model of particle energization in the jet and have found that

the detection of neutrinos from AGN would be possible with future neutrino telescopes of the ICECUBE class, if the γ -ray light curves of blazars are used to define the search windows in data space.

5.1 Which AGN have been observed in TeV γ -rays?

The BL Lacs Mkn 421 and Mkn 501 are now regularly observed by many groups. Both sources are usually so bright that well defined γ -ray spectra can be obtained. Some other BL Lacs have been observed in the past, but haven't been detected in later campaigns or by other groups. An example is 2344+514 which has been detected with WHIPPLE (Catanese et al., 1998), but not with HEGRA, and has now been detected again with WHIPPLE, if with very moderate statistical significance (Badran & Weekes, 2001). The southern BL Lac 2155-304 has not been detected with CANGAROO II in the year 2000 (Nishijima et al., 2001) with a flux limit below the level previously reported (Chadwick et al., 1999). The prototype of the class, BL Lacertae (2200+420) has also not been detected in recent observations (Mang et al., 2001) with a flux limit below the level previously reported (Neshpor et al., 2001). A good candidates though it is, 2005-489 (Nishijima et al., 2001) was not detected as a source of TeV γ -rays.

Recently the BL Lac 1426+428 was detected with WHIPPLE (Horan et al., 2001) and confirmed with HEGRA and CAT (in both cases communicated only at the conference). This source is interesting for its redshift of $z=0.129$ which is about four times that of Mkn 421 and Mkn 501, thus allowing studies of the effect of absorption by the infrared background.

Not detected in TeV scale γ -rays at all to date are radio-galaxies and quasars (LeBohec et al., 2001; Götting et al., 2001).

5.2 Correlation between X-rays and γ -rays

Searches for possible correlations are a standard tool in astronomy when the basic characteristics of sources have to be understood. The multiband spectra of blazars typically show a low energy and a high energy component, which are possibly produced by the same particles through different radiation processes, e.g. synchrotron radiation at low energies and inverse Compton scattering at high energies. It may therefore be useful to compare the lightcurves of blazars at the energies at which the components display their peak in emitted power, namely X-rays and TeV γ -rays.

This can be done for short, but well covered periods of time, an example of which is shown in Fig.6. One particular outburst in TeV γ -rays happens to coincide with one outburst in X-rays without noticeable delay. The figure shows the rising phase and the decay phase of the outbursts, but not the behaviour preceding or following the event. Apparently the X-ray and γ -ray light curves are well correlated for the particular interval of seven hours displayed here. Does that imply that we can speak of a X-ray/ γ -ray correlation? Or

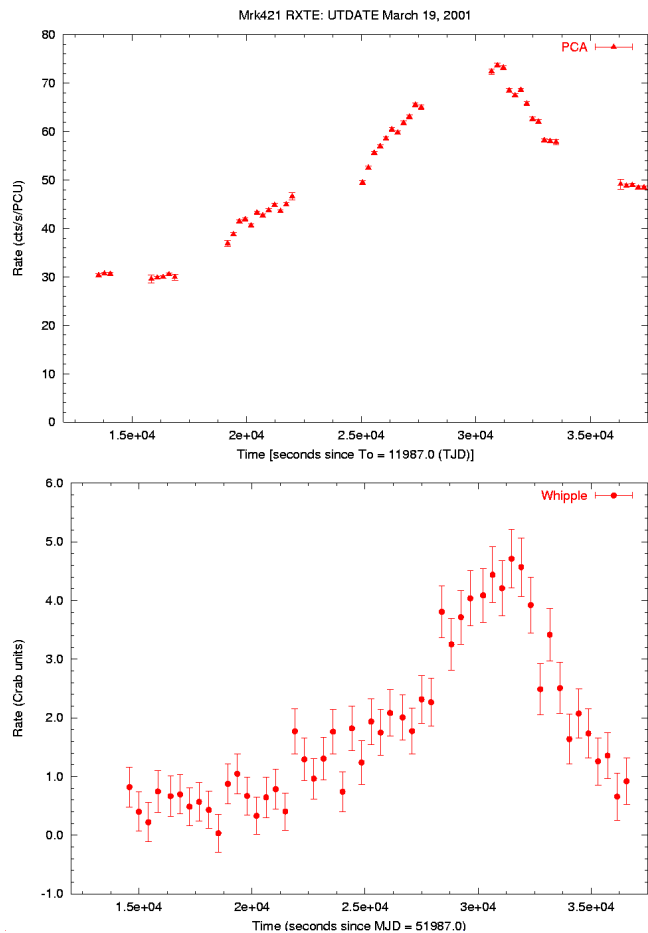


Fig. 6. Simultaneous X-ray/ γ -ray flare observed on March 19, 2001 (taken from Jordan et al. (2001)). The 2-10 keV X-ray light curve was obtained with the PCA detector on RXTE (Fossati et al., 2001). The $E > 300$ GeV γ -ray data were obtained with the WHIPPLE telescope and are binned into 4 min intervals.

are we guilty of sample occulting by selectively showing the data when the fluxes vary in unison? I will come back to this point later.

What conclusion on the physics in the jet of Mkn 421 can be drawn given the rapid outburst displayed in Fig.6? A number of authors have dealt with this subject in their presentations and I repeat the main arguments here. The TeV scale γ -ray outburst has a rise time scale of about one hour and a similar or possibly somewhat shorter decay time scale. The decay is probably related to energy losses and thus to internal processes. Accounting for relativistic beaming by the Doppler factor, D , we find the energy loss time scale in the jet frame as

$$\tau^* = D \tau_{\text{obs}} \simeq 3000 D \text{ sec} \quad (4)$$

The power emitted in X-rays is a significant fraction of the observed bolometric luminosity, therefore under the assumption of a synchrotron origin of the X-rays the electron energy losses can be approximated by those for synchrotron radia-

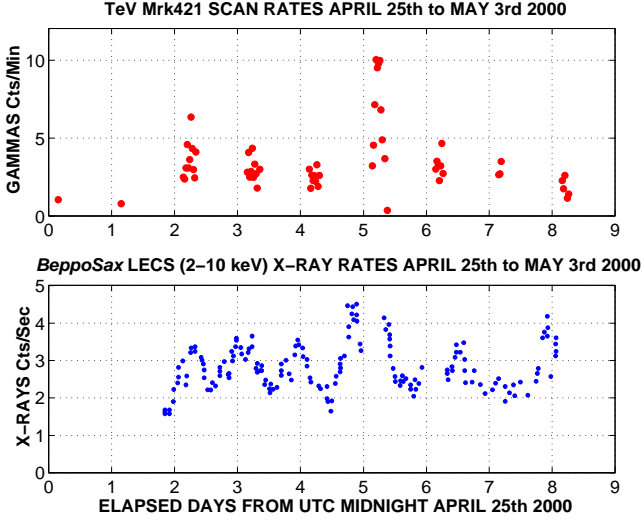


Fig. 7. Contemporaneous Mkn 421 TeV γ -ray and X-ray light curves (taken from Fegan et al. (2001)). The γ -ray data have been obtained with the WHIPPLE telescope. The maxima in the count rates in γ -rays and in X-rays apparently coincide, though the X-ray detector had a dropout at the time of the peak in γ -rays. The variability in X-rays is fairly well resolved, whereas that in γ -rays is clearly undersampled.

tion, yielding

$$\tau_{\text{sy}}(10 \text{ keV}) \simeq 1200 \left(\frac{B}{\text{Gauss}} \right)^{-1.5} \text{ sec} \quad (5)$$

so that

$$\tau_{\text{sy}}(10 \text{ keV}) \simeq \tau^* \Rightarrow B \simeq 0.5 D^{-2/3} \text{ Gauss} \quad (6)$$

For information travel time reasons the source region has a diameter not larger than

$$R^* \leq R_c \approx c \tau^* \simeq 10^{14} D \text{ cm} \quad (7)$$

Given these relations we can ask two questions. What are the source size and magnetic field strength required for the SSC emission not to exceed the observed TeV γ -ray flux? Then, assuming the X-rays are produced in the same volume as are the γ -rays, what is the optical depth of γ -rays for pair production with the X-ray photons?

Let us first deal with the SSC question. In the jet frame the energies of the X-ray and γ -ray photons can be written in units of the electrons rest mass energy.

$$\epsilon_X^* \simeq \frac{0.01}{D} \quad \epsilon_\gamma^* \simeq \frac{10^6}{D} \quad (8)$$

so that the comptonization of X-rays would happen in the Klein-Nishina regime with a cross section reduced by a factor $\sim D^2 10^{-4}$ compared with the Thomson cross section, σ_T . Let us compare the energy density of X-ray photons in the source at the luminosity distance r_L with that of the magnetic field.

$$u_{\text{ph}}^* \simeq \frac{r_L^2}{c D^4 R^{*2}} (\nu F_\nu) \geq \frac{10^5}{D^6} \text{ erg cm}^{-3} \quad (9)$$

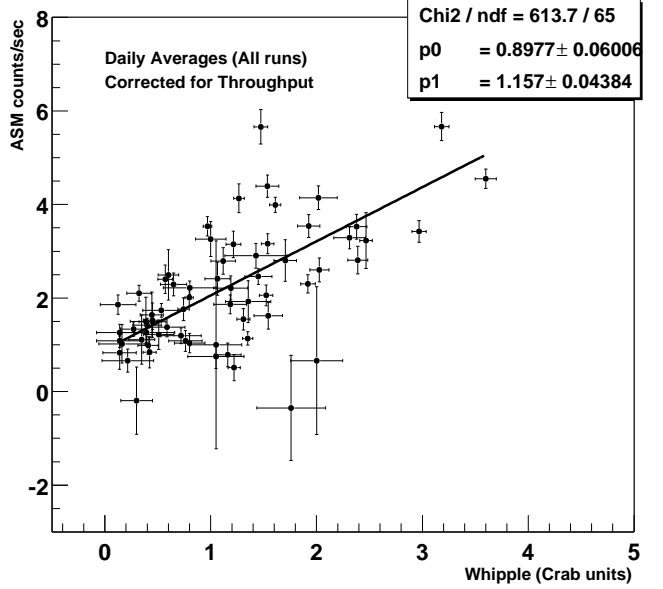


Fig. 8. The correlation of TeV γ -ray rates from Mkn 421 with one-day ASM quicklook count rates in the energy range of 2–12 keV (taken from Holder et al. (2001)). The data shown have been taken between November 2000 and April 2001.

This energy density weighted with the reduction factor for the scattering cross section $\sim D^2 10^{-4}$ must not be larger than the magnetic energy density, otherwise the expected SSC γ -ray flux would exceed the observed flux. This leads to a lower limit for magnetic field strength, which together with Eq.6 gives a lower limit for the Doppler factor.

$$B \geq 15 D^{-2} \text{ Gauss} \Rightarrow D \geq 13 \quad (10)$$

Please note that D could be smaller if the synchrotron energy loss time scale is smaller than the flare decay time scale (Eq.4). Eq.8 indicates that for Doppler factors $D \leq 100$ the γ -ray photons can produce pairs by collisions with the X-ray photons with a cross section of the order of $\sigma_p \simeq D^2 \sigma_T 10^{-4}$. The optical depth is approximately

$$\tau_p \simeq \frac{u_{\text{ph}}^* R^* \sigma_p}{\epsilon_X^* m_e c^2} \geq 0.1 D^{-2} \quad (11)$$

so that internal absorption on the X-ray photons is not important, unless $R^* \ll R_c$. This does not exclude the possibility of absorption by pair production with optical or UV photons. It should be noted that the conclusions we have derived are not based on the assumption of a specific radiation process for the TeV scale γ -rays.

Let us now return to the question whether or not a single, correlated outburst can be taken as evidence for a correlation between different wavebands. Fig.7 shows the X-ray and γ -ray light curves of Mkn 421 for a week in the year 2000. The X-ray light curve is essentially continuous, except for two detector dropouts, one of which occurred at the time of the peak in γ -rays. The γ -ray measurements have taken place only during the night, for an imaging atmospheric Čerenkov telescope has been used.

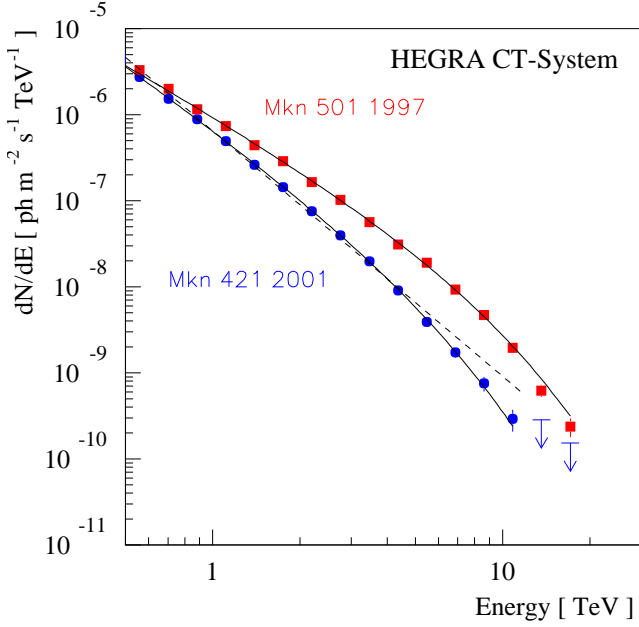


Fig. 9. The Jan/Feb 2001 time-averaged Mkn 421 γ -ray spectrum as observed with HEGRA as well as the 1997 time-averaged spectrum of Mkn 501 (taken from Kohnle et al. (2001)). The solid line shows the fit of a power law with exponential cut-off, the dashed line shows a single power law fit. Upper limits are 2σ confidence level.

The variability in X-rays appears to be fairly well resolved. In a Fourier spectrum of the light curve most of the power would reside at time scales of 10–20 hours and very little at smaller time scales. In γ -rays that is obviously different: most of the power in a Fourier spectrum would reside at time scales around one hour and very little at longer time scales, except perhaps for the outburst on day 5. Clearly, there is no one-to-one correlation between X-rays and TeV γ -rays.

Holder et al. (2001) have compared the WHIPPLE light curve for Mkn 421 between November 2000 and April 2001 with the RXTE ASM light curve of keV scale X-rays. Fig. 8 shows a scatter plot of the respective counts rates. Obviously, a linear regression provides a pretty bad fit. There is certainly a trend, that on days with a high γ -ray rate the X-ray rate is also enhanced, but the relative scaling varies quite a lot. I don't know what the underlying process is. But I do know what the underlying process is not: it is not synchrotron-self-Compton scattering in a homogeneous source. This implies that all deductions of physical parameters based on the assumption of a simple SSC model are of limited value, for the model doesn't apply.

5.3 The TeV scale γ -ray spectra of AGN

Earlier measurements indicated that the TeV γ -ray spectrum of Mkn 501 is curved, possibly caused by absorption, and that the spectrum of Mkn 421 up to γ -ray energies around 10 TeV is well described by a single power law. That was disturbing, because at 5 TeV or higher an effect of absorp-

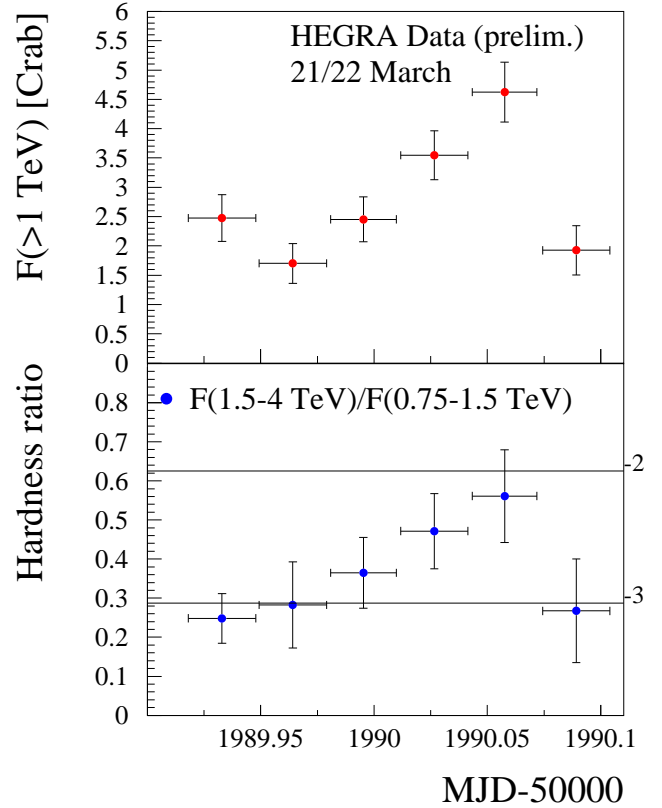


Fig. 10. The TeV γ -ray rate from Mkn 421 and the hardness ratio observed with the HEGRA array during the night of March 21/22, 2001 (from a viewgraph presented by D. Horns). The γ -ray spectrum is apparently harder when the count rate is high.

tion on the infrared background should have been visible on account of lower limits on the infrared photon density in intergalactic space. Of all imaging atmospheric Čerenkov telescope operational to date, HEGRA offers the best energy resolution. Recent measurements have shown, that also the Mkn 421 γ -ray spectrum displays curvature (Kohnle et al., 2001). Fig. 9 clearly shows that the spectrum observed in early 2001 cannot be represented by a single power law. The cut-off energy for a power law with exponential cut-off is $E_0 = (4.2 - 0.4 + 0.6)$ TeV, the power law index is $s = 2.33 \pm 0.08$. This curved spectrum is compatible both with data taken earlier and the results of WHIPPLE and CAT. The best fit to the γ -ray spectrum of Mkn 501 is obtained for $E_0 = (6.2 \pm 0.4)$ TeV and $s = 1.92 \pm 0.03$. The power law index and the cut-off energy are statistically not completely independent of each other. Nevertheless, it is clear that the TeV scale γ -ray spectrum of Mkn 501 is harder than that of Mkn 421.

For models of γ -ray production in AGN it usually is an easy exercise to reproduce the spectrum observed at a given time. Also, the observed time scales of the variability are not problematic for the theories. However, the models make fairly different predictions for how flares would evolve at different γ -ray energies. Clearly, what has been lacking so far as constraint for the theories are observations of spec-

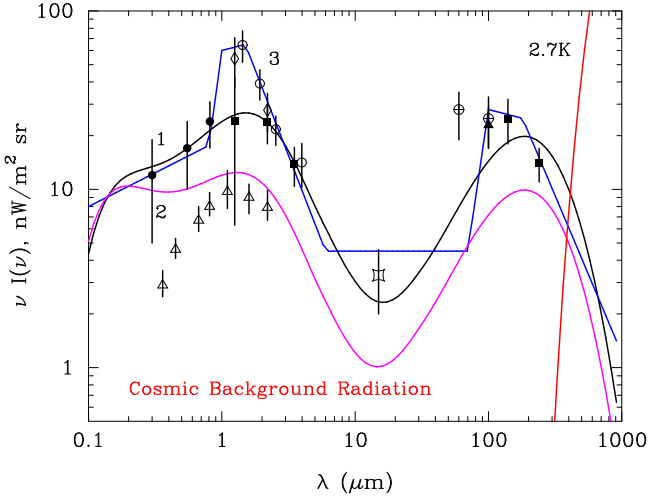


Fig. 11. Three test spectra of the infrared background radiation shown in comparison with actual measurements (from a viewgraph presented by N. Götting). The triangles are effectively lower limits from resolved sources, as is the point at 15 μm . The other data are from absolute photometry and may contain foreground emission which has not been properly subtracted.

tral variability. This may change in the near future. Preliminary though the analysis is, at this conference the HEGRA team has presented the first credible evidence for a hardening of the γ -ray spectrum of Mkn 421 during an outburst (see Fig.10).

5.4 γ -ray absorption by the infrared background

High energy γ -rays can interact with ambient radiation and form an electron/positron pair

$$\gamma + \gamma \rightarrow e^+ + e^- \quad (12)$$

The electrons would also be highly relativistic and would emit γ -rays at energies somewhat smaller than the energy of the primary γ -ray that has produced the pair. The secondary γ -rays would be emitted at a small angle with respect to the primary γ -ray, even if the electron was not significantly deflected by magnetic fields. Essentially, the γ -radiation cascades to lower energies and at the same time is scattered out of the line-of-sight. For the γ -ray flux from a point source this process corresponds to an absorption, with the radiation energy reappearing in the form of diffuse emission.

The pair production rate for an isotropic distribution of soft target photons peaks at a few times the threshold energy, defined by $E_{\gamma_1} E_{\gamma_2} = 0.25 m_e^2 c^4$, and falls off rapidly for higher interaction energies. The target photons responsible for the absorption of TeV scale radiation are thus in the infrared range. Fig.11 shows models and data of the extragalactic infrared background light (for a comprehensive review see Primack et al. (2001)). Apparently, our knowledge of the actual intensity of the infrared background is accurate only to a factor of around two, depending on wavelength. The HEGRA team has used three possible test spectra of the

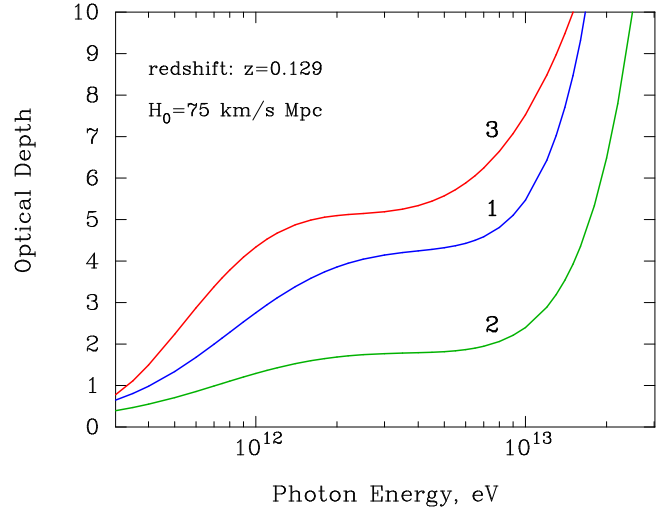


Fig. 12. The optical depth for γ -rays as a function of energy for the three model spectra of the infrared background shown in Fig.11 (from a viewgraph presented by N. Götting). The assumed redshift of the source is that of 1426+428.

infrared background to estimate the optical depth for TeV γ -rays from AGN and the uncertainty thereof. Spectrum 1 follows closely the model of Primack et al. (2001) for a Kennicutt-IMF (initial mass function of stars). Spectrum 2 is close to the lowest intensity allowed by the actual data. Spectrum 3 has been devised to reproduce recent measurements of very intense near-infrared background emission (Matsumoto, 2000; Cambr  s et al., 2001). Fig.12 shows the optical depth thus determined for the recently detected BL Lac 1426+428 for the three model spectra of the infrared background light.

Rather than correcting the observed γ -ray spectra of AGN for the effect of absorption, one can use models of the intrinsic γ -ray spectra, calculate the γ -ray spectra after attenuation by the cosmic background radiation, and compare those with the measured spectrum. Two groups (G  tting for the HEGRA team, and Vassiliev for the VERITAS collaboration) have independently presented such calculations, one assuming an intrinsic spectrum following a power law of arbitrary index, the other one assuming a power law with a fixed index of 1.92 based on an SSC origin of the γ -rays.

At this conference the HEGRA team has presented a preliminary γ -ray spectrum of 1426+428, which appears to be surprisingly well defined given the statistical significance of the detection as such. As shown in Fig.13, none of the three models of the cosmic infrared background is in conflict with the data. Preliminary though they are, the results suggest that the intrinsic γ -ray spectrum of 1426+428 is harder than a power law E^{-2} up to about 10 TeV. Clearly, a better defined γ -ray spectrum must be measured before definitive conclusion can be made. Nevertheless, with the confirmed detection of an AGN at a redshift of $z \simeq 0.13$ meaningful studies of the cosmic infrared background radiation become feasible by means of TeV γ -ray astronomy.

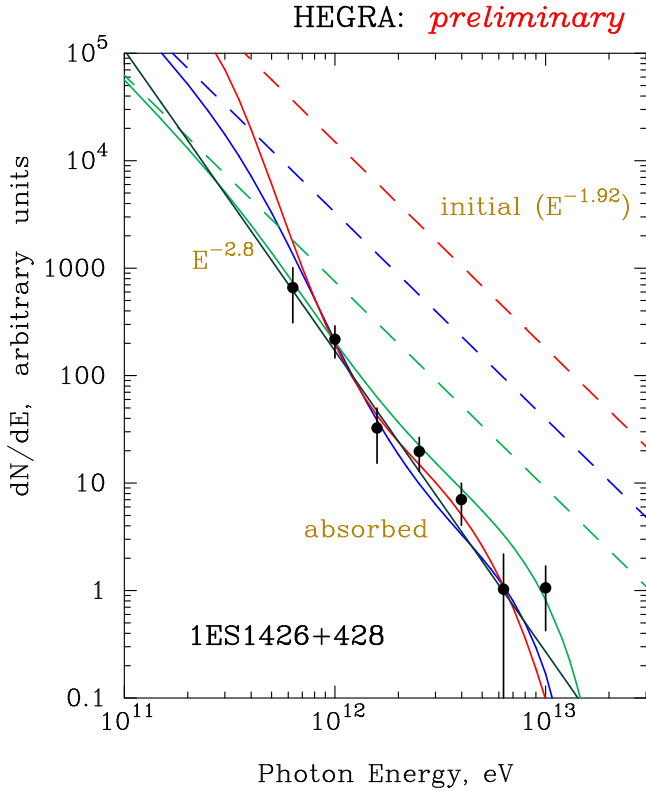


Fig. 13. The preliminary spectrum of 1426+428 as measured with the HEGRA array in comparison with model spectra (from a viewgraph presented by N. Götting). For the three models of the infrared background shown in Fig. 11 the attenuation of an assumed intrinsic power law γ -ray spectrum is calculated. Apparently none of the three models is in conflict with the data.

Fig. 12 indicates that the optical depth for γ -rays increases rapidly for photon energy beyond 10 TeV, whatever the actual model of the infrared background. Even for Mkn 421, which resides at a quarter of the distance of 1426+428, the optical depth at 20 TeV would be $\tau_2 \simeq 1.3$ for spectrum 2 and $\tau_{1,3} \approx 5$ for the spectra 1 and 3 of the cosmic background radiation. Measurements at energies around 10 TeV or higher can be performed with the imaging atmospheric Čerenkov telescopes, when the source is far from the zenith, for both the threshold energy and the effective area are then much higher than near zenith. Such measurements have recently been performed with CANGAROO II, and the result of a preliminary analysis is shown in Fig. 14. Up to the highest data point, which represents γ -rays around 35 TeV, no effect of attenuation is visible in the spectrum, though the optical depth should be much higher than unity for all possible models of the infrared background. Consequently, the intrinsic γ -ray spectrum of the source would have to be extremely hard beyond 20 TeV, if the two data points at the highest energy were correct. The analysis of the CANGAROO data is still preliminary, and thus the results may change beyond what is indicated by the error bars. These results can be best summarized by stating that they represent either a problem with the data analysis or a scientific sensation, for

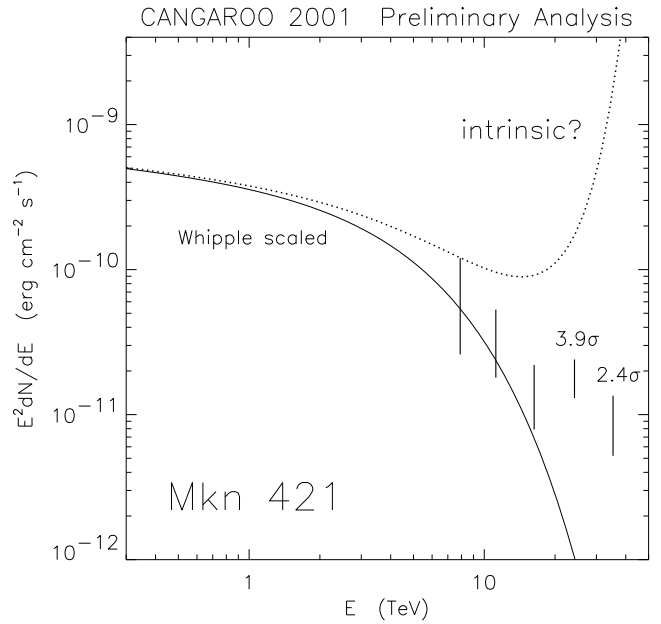


Fig. 14. The Mkn 421 γ -ray spectrum observed at large zenith angle with CANGAROO II after preliminary analysis (according to a viewgraph presented by K. Okumura). The scaled average spectrum observed with WHIPPLE in 2001 is shown as the solid line for comparison. Given the high optical depth for photon energies beyond 20 TeV, the intrinsic spectrum would have to look roughly like the dotted curve, if the two data points at the highest energy were correct.

something would have to be seriously wrong in our understanding of the universe, may it be Lorentz-invariance or the relation between redshift and distance or something else.

6 Gamma-ray bursts

Several models of Gamma-ray bursts (GRBs) predict TeV scale radiation from inverse Compton scattering or other processes with comparable fluence to the well measured MeV scale radiation (e.g. Dermer, this volume). Measuring the VHE component of GRBs may be critical to the understanding of the charged particle acceleration. However, the detection of TeV emission from GRBs is complicated by the attenuation of VHE photons by interaction with the intergalactic infrared radiation, for which the optical depth is around unity for a redshift of $z = 0.1$ at TeV γ -ray energies.

Sensitive though the atmospheric Čerenkov telescopes are, their field-of-view and duty cycle are too small to provide a good coverage of the prompt emission from GRBs detected by other resources such as BATSE. The air shower arrays are much better suited to search for TeV emission from known GRBs. However, the INCA and TIBET arrays have not found a γ -ray signal coincident with BATSE bursts (Amenomori et al., 2001c; Castellina et al., 2001). It should be noted that the altitude of INCA and the use of the "single particle" technique have allowed to work with a detection threshold of a few GeV. MILAGRO has conducted a search for GRBs with-

out any prior knowledge of the bursts position in the sky, its start time and duration, which yielded no detection (Smith et al., 2001). Given the temporal and spectral coverage of the searches performed so far, the one γ -ray excess coincident with a BATSE burst that was found by MILAGRITO (Atkins et al., 2000), the smaller prototype of MILAGRO, has a significant probability of having occurred by chance.

It is usually presumed that the afterglow emission of GRBs is caused by the sweep-up of interstellar matter by the decelerating relativistic blast wave. Meli & Quenby (2001) have numerically investigated shock acceleration of particles in this environment. They find that for highly relativistic blast waves ($\Gamma \geq 100$) structured particle spectra would be produced, which significantly differ from power laws. If $\Gamma \sim 1000$ proton acceleration to $\sim 10^{20}$ eV could be possible, which, if the protons would escape from the system without losing their energy, could be one possible source of ultra-high energy cosmic rays (Vietri, 1995; Waxman, 1995).

7 Summary

To date, a wealth of new exciting data is available in γ -ray astronomy, for a number of observatories using the imaging atmospheric Čerenkov technique are operational and provide a very good flux sensitivity per source. The prospects for the future are equally bright: four new imaging atmospheric Čerenkov telescope are under construction, which will allow observations with a better flux sensitivity and a lower energy threshold than possible to date. With the advent of the forthcoming satellite-based GLAST experiment in a few years from now coordinated measurements at γ -ray energies between 50 MeV and 20 TeV will be possible.

The data available to date have considerably furthered our understanding of the high energy sky.

- Measurements of diffuse TeV scale γ -ray emission start to constrain models, in particular those devised to explain the GeV excess in diffuse galactic γ -ray emission.
- There is still no unambiguous evidence of cosmic ray nucleon acceleration in SNR or other possible sources of galactic cosmic rays.
- The accuracy of the measurements is such that studies of spectral evolution during short-time γ -ray outbursts of AGN become feasible, thus constraining models of particle energization in these objects.
- TeV γ -ray emission has been observed from a number of AGN ranging from ~ 0.03 to ~ 0.13 in redshift, thus allowing to commence studies of the infrared background light by disentangling the intrinsic γ -ray spectra of AGN and their modification by γ -ray absorption through pair production in intergalactic space.

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their results in electronic form, in some cases when those were still preliminary. Some results presented at the conference were obtained after the submission deadline for contributed papers. It is possible that my recollection of results presented only as talks or posters and not as papers is incomplete. Therefore I would like to apologize to everyone who finds his work misinterpreted in this rapporteur paper. I did my very best.

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